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Naval Submarine Medical Research Laboratory
Groton, Connecticut

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by

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Bureau of Medicine and Surgery, Navy Department
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13 ABSTRACT

Recorded speech tests were passed through 16 low-fidelity speech communication circuits, rated from good to poor, and listening panels underlined the key words heard. Mean scores among circuits (hearing aids) ranged from 53 to 75 per cent words correct. A total of 32 indices of electroacoustic characteristics was obtained or derived from measures of: transient, harmonic, intermodulation and frequency distortion; gain; and signal/noise ratio. Each index was correlated with speech intelligibility, and multiple correlations were derived for optimal prediction of speech intelligibility from a knowledge of the physical characteristics of any circuit. The optimal prediction (Multiple R=.65) was obtained from (1) extended low-frequency response, (2) high average gain for white noise, (3) smooth frequency-response curve, plus (4) low transient distortion. An equally good predictor was found, (r=.64) for cubic intermodulation distortion at 2 kHz, but in the illogical direction that greater (worse) distortion was found in the more intelligible aids. From this paradox it appears that a complex relationship exists among distortions such that the route by which, for example, cubic intermodulation influences intelligibility depends upon a given pattern of possible correlations among indices. These complex patterns have not here been identified for the 16 circuits separately.

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SUMMARY PAGE

THE PROBLEM:

To determine the intelligibility obtained through a low-fidelity communication circuit (intercom, helmet radio hearing aid, etc.) from a study of its physical characteristics.

FINDINGS:

Thirty-two indices of physical characteristics were determined for each of 16 circuits. Prediction of speech reception was fair (Multiple R=.65) by combining measures of (1) low-frequency response, (2) gain, (3) smoothness of frequency-response, plus (4) transient distortion. The data show that to achieve better prediction in subsequent studies it will be necessary to identify rather complex patterns of electroacoustic characteristics.

APPLICATIONS:

For the use of communications engineers designing speech communications systems in which restrictions of weight, size, and cost lead to compromises in fidelity, and for human factors specialists assessing system inefficiencies traceable to speech communications breakdowns.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Bureau of Medicine and Surgery Research Work Unit MF51.524-004-9010DA5G. The present report is No. 18 on this Work Unit. It was approved for publication on 8 May 1972, and designated as NAVSUBMEDRSCHLAB Report No. 707.

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ABSTRACT

Recorded speech tests were passed through 16 low-fidelity speech communication circuits, rated from good to poor, and listening panels, consisting of Naval Submarine School students, underlined the key words heard. Mean scores among circuits (hearing aids) ranged from 53 to 75 percent words correct. A total of 32 indices of electroacoustic characteristics was obtained or derived from measures of: transient, harmonic, intermodulation and frequency distortion; gain; and signal/noise ratio. Each index was correlated with speech intelligibility, and multiple correlations were derived for optimal prediction of speech intelligibility from a knowledge of the physical characteristics of any circuit. The optimal prediction (Multiple R=.65) was obtained from (1) extended low-frequency response, (2) high average gain for white noise, (3) smooth frequency-response curve, plus (4) low transient distortion. An equally good predictor was found, (r=.64) for cubic intermodulation distortion at 2 kHz, but in the illogical direction that greater (worse) distortion was found in the more intelligible aids. From this paradox it appears that a complex relationship exists among distortions. For example, the route by which cubic intermodulation influences intelligibility depends upon a given pattern of possible correlations among indices. These complex patterns have not been identified for the 16 circuits presented in this report.

ACKNOWLEDGMENT

The research reported herein by the investigator, Mr. J. Smaldino, was carried out in the Auditory Branch of the Naval Submarine Medical Research Laboratory. These research findings were submitted by Mr. Smaldino to the Department of Speech, University of Connecticut, as a dissertation for the graduate degree of Master of Science in Audiology.

Doctor J. D. Harris, head of the Physiopsychological Sciences Division, Naval Submarine Medical Research Laboratory, assisted Mr. Smaldino in the conduct of his research and served as his thesis advisor.

G. F. GELL, M.D., D.Sc.(Med)
SCIENTIFIC DIRECTOR

THE EFFECT OF ELECTROACOUSTIC CHARACTERISTICS OF LOW-FIDELITY CIRCUITRY UPON SPEECH INTELLIGIBILITY

INTRODUCTION

In recent years, investigators have considered the correlation between the electroacoustic characteristics of voice communication circuits and the intelligibility of speech signals passed through them. Several kinds of electroacoustic characteristics have been identified in, for example, the hearing aid (Kasten and Lotterman[26]; Kasten, Lotterman and Revoile[25]; Lotterman and Farrar[33]; Lotterman and Kasten[34,35]; Davis[10]; Davis et al[11]; Zerlin and Burnett[59]; Le Bel[27]; Lybarger[36, 37, 38]; ASHA Report[1]; Nichols[40]) some of which are termed non-linear to designate that the input signal to the hearing aid has been changed by the aid and is different in quantifiable ways from the output signal. The detrimental effects upon the perception of speech by these changes or distortions have not been unanimously ascribed to any one distortion, partly because of an inadequate appraisal of the effects of distortion interactions.

This study was designed to investigate the effects of various electroacoustic characteristics and non-linear distortions, alone and as aggregates on the intelligibility of speech.

A. Review of Literature

The electroacoustic characteristics that have been implicated as detrimental to speech intelligibility include: width of the frequency response curve (bandwidth), regularity of the frequency response curve, harmonic distortion, intermodulation distortion and performance characteristics designed to quantify the effect of distortion interactions, namely, transient distortion and total intermodulation distortion.

Although not in agreement as to the single most important characteristic to intelligibility, the research cited in support of the above characteristics suggested, in part, the direction and need for the present investigation.

1. Width of the Frequency Response Curve (bandwidth).

The electroacoustic characteristics of the microphone, amplifier and receiver of a hearing aid interact so that the gain across frequencies is not constant, as is shown in the usual frequency-response characteristic. There are several standard methods whereby the low and high frequency limits of the bandwidth can be routinely specified; some of these will be detailed below. The importance of the bandwidth to speech intelligibility has been suggested by several investigators:

Olsen and Carhart,[42] while investigating the usefulness of some test procedures on the evaluation of binaural hearing aids, discovered that speech discrimination was reduced when heard through a hearing aid, when compared with direct reception at comparable signal to noise ratios. This finding led the investigators to explore the effects of bandwidth, harmonic distortion and

intermodulation distortion of three hearing aids on speech intelligibility. It was found that bandwidth was the only electroacoustic characteristic which consistently rank-ordered the aids in the same way as speech discrimination.

Olsen found, in 1971,[36, 37] that aids having the least difference in frequency intermodulation distortion (C. C. I. F. method, described in Procedure section) and broadest bandwidth, produced the best discrimination scores when persons with sensory-neural hearing losses were tested. In attempting to determine whether the effect on discrimination was due to intermodulation distortion or bandwidth, he conducted a study in which harmonic and intermodulation distortion could be varied (using a peak clipper) and where other performance characteristics could be held relatively constant. Persons with sensory-neural hearing losses and excellent speech discrimination in quiet were tested, in quiet, with competing message and with presence of amplitude modulated white noise. Speech discrimination, in quiet, was not changed even with large amounts of harmonic and intermodulation distortion; in the competing message condition scores were slightly improved, while a slight reduction in performance was noted in the amplitude modulated white noise condition. None of these results are especially remarkable, for it has been substantially documented that even severly clipped speech continues to be highly intelligible, and, indeed, can be more intelligible than speech not limited by peak clipping with high frequency emphasis or filtering (Thomas and Neiderjohn[52]; Thomas and Neiderjohn[53]; Thomas and Sparks[54]. Licklider[31]; Licklider and Pollack[32]).

2. Regularity of the Frequency Response Curve.

Jerger and Thelin[23] in assessing hearing aids for speech understanding. looked at the shape of the frequency response curve, effective bandwidth, harmonic distortion, gain, signal-to-noise ratio and signal-to-hum ratio. A strong correlation was found between speech understanding, as measured by the Synthetic Sentence Identification Test (SSI) (Speaks and Jerger[51]) and "irregularity of frequency response." In other words, the aids which produced the best speech scores had the smoothest frequency response curves. An index of response irregularity (IRI) was devised which was "roughly proportioned to the jaggedness or overall departure from smooth uniform slope in the frequency response" and which showed the best correlation with SSI scores than any other electroacoustic characteristic investigated. It was found that the next highest correlation with SSI scores was the bandwidth below 1 KHz and that harmonic distortion was "not implicated in the degradation in speech understanding in modern hearing aids," indeed, SSI scores tended to be better in those aids showing the greatest distortion.

3. Harmonic Distortion.

If a pure tone of frequency f_0 is passed through a linear electroacoustic system, the output will contain only the f_0, with, perhaps, phase and amplitude differences (Davis and Silverman[12]). If the electroacoustic system is nonlinear, as in most hearing aids, harmonics of

the input pure tone frequency 2 f_0, 3 f_0 ... will also be present in the output. Because the frequency range of a hearing aid defines the high and low frequency limits of amplification and acts as an effective filter, low fundamental frequencies will thus generate more measurable harmonics than high frequencies, because it is probable that more of the former are within the effective bandwidth of the hearing aid. The presence of these harmonic components of the f_0 within the limits of amplification of a hearing aid is termed harmonic distortion.

Jerger, Speaks and Malmquist[21] attempted to discover a performance task that would reliably distinguish among hearing aids and then to determine whether rankings of performance of hearing aids yielded with a sentence intelligibility test, could be duplicated with the standard monosyllabic word lists. Results showed that while sentence intelligibility tests with intellective masking rank-ordered the aids in inverse proportions to harmonic distortion, "performance differences were not systematically reflected in the monosyllabic word test result", presented in quiet.

Bode, et al,[7] using 34 normal-hearing listeners found that consonant discriminations were reduced over a range of 13-30% with increasing harmonic distortion (5%, 15%, 25%, 35%).

Bode and Kasten[8] invoked reduced high-frequency response and altered speech-to-noise ratio, in concert with harmonic distortion, as causes for reduced consonantal differentiations.

Harris, et al[16] in exploring the effects of signal-to-noise ratio, frequency range, flatness of the frequency response curve, harmonic distortion and intermodulation distortion upon intelligibility of speech passed through a hearing aid, found harmonic distortion correlated best with speech intelligibility error scores. Intermodulation distortion was also implicated as being important to speech intelligibility, but correlated so strongly with harmonic distortion, that its importance was suggested to have arisen from this relationship. Other conclusions were that, (a) harmonic distortion must be on the order of 20% to significantly degrade intelligibility, (b) that cubic or quadratic intermodulation distortion is not a factor in intelligibility, (c) that frequency range is only slightly correlated with intelligibility, (d) that an improvement in the signal-to-noise ratio over +25 dB does not increase intelligibility, and (e) that the area under an aid's frequency response curve is a moderately good predictor of intelligibility, although no aid investigated by them approached the minimum area where intelligibility would become negligible. Finally it was suggested (f) that transient distortion is, perhaps, the most important portender of intelligibility, although instrumentation for this measurement was at that time wanting.

4. Transient Distortion.

Speech is a transient signal, it is composed of rapidly rising and falling formants of energy, followed by silent periods. Because of physical and electroacoustic limitations, various com-

ponents of a hearing aid are unable to follow some of the rapid transient changes in energy. The result is that these rapid changes are not followed faithfully, by the hearing aid, so that the output waveform and temporal characteristics do not correspond to the input signal. Such a smearing of the signal is termed transient distortion.

It has been suggested previously that transient distortion may be the most detrimental electroacoustic characteristic to speech perception (Harris, et al[16]; Olsen[42]) and, indeed recent evidence as to the importance of formant transitions to the perception of the speech code (Liberman[29, 30]) encourage such a hypothesis. Until the study of Witter and Goldstein[58], however, the production of an acoustic square wave had been electroacoustically crude. The importance of a square wave in the quantification of transient distortion in a hearing aid, lies primarily in its rapid rise and fall times which are physical characteristics of formant transitions. Since these transients appear to carry important parameters to speech perception, a study of changes effected by a hearing aid on a square wave, may provide predictive information as to how well speech will be understood through that aid.

Witter and Goldstein[58] assumed a result by Zerlin[60] which indicated that while intelligibility test results did not differentiate electroacoustically different hearing aids, listeners' preference judgments did and that these judgments were in some way reflective of measured electroacoustic characteristics. Using this latter assumption, Witter and Goldstein correlated preference judgments with five aids, which provided a range of values on harmonic distortion, intermodulation distortion, frequency range, and the amount of change introduced by a hearing aid on an approximation of an acoustic square wave. Transient distortion correlated better with the preference judgments, then frequency range and harmonic distortion. Intermodulation distortion had little effect on the quality judgments. While the ranking of these characteristics is contrary to some previously mentioned studies, it should be remembered that these are preference judgments and not intelligibility scores. In conclusion, it was stated that disagreement as to the important electroacoustic characteristic to speech in previous studies may have been caused by interaction of various characteristics and that transient response, being an indication of overall linearity (interaction effect) in an electroacoustic system, may be the most appropriate single measure of effect an aid will have on intelligibility.

5. Interaction of Electroacoustic Characteristics.

Another method of getting at the overall interaction of nonlinearities in an electroacoustic system has been suggested (Burnett and Priestley[4]; Burnett[5, 6] and Corliss et al[9]). By using a speech-noise test signal (shaped to approximate the peak power of speech), notching out a bandwidth with a reject filter, passing it through a hearing aid and measuring the acoustic products of the notched bandwidth in the output, the effects of all concomitant nonlinear interactions can be quantified. The major limitation of this speech-noise inter-

modulation test is that nonlinear interaction cannot be measured as a function of input frequency; this restricts its use as a design characteristic for future hearing aids.

Correlation of this speech-noise intermodulation test with conventional pure-tone harmonic distortion tests is low and suggests that the harmonic test is "inadequate for predicting the distortion that occurs in a hearing aid with a complex input signal" (Burnett[5]).

6. The Speech Intelligibility Test.

There has occurred, recently, a reawakening of interest in sentence tests to measure speech intelligibility. For several reasons, a sentence more closely approximates the parameters of speech present in conversation, than single unrelated monosyllabic words (Giolas[13]), and, therefore, has greater validity in assessing a person's communication efficiency. Suggestions as to the nature of the important parameters to speech intelligibility have been made, and include: prosodic features (stress, intonation patterns, etc.) (Lehiste and Peterson[28]); the "transitions in connected discourse from one phoneme to another" (Harris[15]); duration of the message set (Jerger and Speaks[22]); and context conditioned variation and parallel transmission of acoustic cues to the entire sentence (Liberman[29]).

The sentence, then, appears to be our best available predictor of the success a person will have in understanding conversational speech. To this end, the Kent State University Speech Discrimination Test was chosen. It employs five phonetically similar key words embedded in each of thirteen sentences. In the test the speaker reads each test sentence using one of the key words, and the listener's task is to indicate which of the five key words was spoken (Berger[2]). The test has been compared with the CID W-22 PB lists (Berger, et al[3]) and correlated poorly, although the W-22's correlated better with measures of hearing sensitivity than the KSU test. It was concluded, therefore, that, "while the W-22 lists are sensitive for testing hearing impairment", the KSU test presumably predicts more accurately how efficiently one (a person) can utilize his hearing for daily communication purposes. Since this test seems to be useful in predicting success a person will have in using the parameters of speech, it was hoped that it would also be effective in differentiating the use of these same parameters influenced by the nonlinearities of a hearing aid.

B. Purpose of the Study

The literature is not unanimous in specifying what electroacoustic characteristics of a communications circuit functions best for speech intelligibility. Several investigators (Harris[16]; Witter and Goldstein[58]) have suggested that a measure of overall nonlinearity of an electroacoustic system would be a better predictor of the intelligibility of speech passed through the system, than the absolute appraisal of any one nonlinearity. Until the paper by Burnett presenting the speech-noise intermodulation test, transient distortion measures offered the only measurement of overall nonlinearity. Since the production of an

acoustic square wave, necessary for transient distortion measurement has been, at best, difficult, the speech-noise intermodulation test looms as the most easily measured quantification of distortion interaction effects across the frequency response of a communications circuit.

In this paper, many of the nonlinearities and other electroacoustic characteristics investigated by others will be measured and correlated with speech passed through each of 16 communications circuits, the outputs being appraised for intelligibility by the KSU speech discrimination test. The intelligibility scores obtained from this test, when correlated with circuits varying as to measures on nonlinearity, the speech-noise intermodulation test and transient response, will provide a clearer picture of how best to assess the electroacoustic characteristics of communications circuit.

PROCEDURE

A complete description of all procedures is given by Smaldino (1972). Briefly, 16 hearing aids of various brands and vintages were used, each aid assessed by the following:

A. Electroacoustic Characteristics

(1) Frequency Response, Saturation Output, Gain, Average White Noise Gain, and Average Signal-to-Noise Ratio.

The hearing aid under test was placed in a Bruel and Kjaer (B&K) type 4212 hearing aid test chamber (see Fig. 1, Smaldino[50]). A 1 KHz tone was generated by a B&K type 1022 beat frequency oscillator and introduced into the test chamber by a speaker. The receiver of the hearing aid was coupled to a B&K pressure condensor microphone by a 2 cc coupler, the output of which was read in dB on a B&K type 2112 audio frequency spectrometer. The voltage output of the oscillator was increased until with full gain on, the output of the hearing aid did not increase with a further increment in voltage. This point was obtained at 500 Hz, 1 kHz and 2 kHz. The average of these three frequencies was termed the saturation output (maximum power output) of the test aid and the difference in dB between this measure at 1 kHz and a 70 dB input signal at 1 kHz specified the gain of the instrument. The white noise gain was specified in a like manner to the gain, where it was the difference in dB between a 70 dB white noise input to an aid and the white noise saturation output for the average of .5, 1 and 2 kHz.

The voltage of the oscillator was then reduced so that the free field level of a 1 kHz tone in the test chamber was 70 dB SPL. A second B&K condenser microphone was adjacent to the hearing aid microphone and acted as the monitor of a compression circuit made up of a B&K type 2603 microphone amplifier and the oscillator. The function of this cybernetic system was to keep the free field sound level constant at 70 dB SPL at the face of the hearing aid microphone. The gain control of the test aid was then set at a level of 6 dB below its saturation output level, with the 70 dB 1 kHz tone as the reference frequency. The signal-to-noise ratio was computed by shutting off the oscillator set at .5,

1 and 2 kHz respectively for each aid. The remaining energy in dB was compared with the 70 dB input signal and specified the signal-to-noise ratio. The average of .5, 1 and 2 kHz was termed the average signal-to-noise ratio.

The oscillator was then automatically swept through the frequency range 10 Hz - 10 kHz and the relative gain of the aid for each frequency recorded in dB versus frequency on a B&K type 3205 graphic level recorder. This plot was called the frequency response curve for the test instrument (see Figs. 8-23 of Smaldino[50]. The response of the B&K 4212 hearing aid test chamber with a 70 dB input was flat ±2 dB through 6 kHz.

(2) Index of Response Irregularity

This parameter was measured as described by Jerger and Thelin[23] from the frequency response curve of each test instrument. A reference line was drawn parallel to the frequency axis at the lowest reversal of the response curve of more than 2.5 dB. Parallel lines were then drawn at 2.5 dB intervals above this reference. The number of crossings of these parallel lines with the response curve, above the reference, were counted and termed the index of response irregularity for that aid.

(3) Bandwidth

This parameter is the range of frequencies in which the hearing aid provides effective amplification. It is specified by a low and high frequency limit of amplification.

(a) Hearing Aid Industry Conference (HAIC) Procedure

This measure was obtained from the graph of the frequency response curve (Berger[2]; Lybarger[36, 37, 38]). The ordinate values in dB for 500 Hz, 1 kHz and 2 kHz are averaged and plotted on the 1 kHz ordinate. Another point is then plotted on the 1 kHz ordinate 15 dB below the first. A straight line is then drawn through this point parallel to the frequency axis. The low and high frequency limits of amplification for that aid are the frequencies where this line first intersects the frequency response curve, moving in the direction of decreasing and increasing frequency, respectively, from 1 kHz.

(b) Houston Speech and Hearing Center (HSHC) Procedure

This measure was also obtained from the frequency response curve of a hearing aid (Jerger and Thelin[23]): A line was drawn "parallel to the frequency axis at 10 dB below the highest point on the response curve." The low and high frequency limit of amplification of the test aid was defined as the frequency where the parallel line first intersected the response curve, moving in the direction of decreasing and increasing frequency, respectively, from 1 kHz. In two of the aids, the bandwidth specified this considerably below 1 kHz, however, it was negative, because the lowest point intersected by the parallel line on the frequency curve was above 1 kHz.

For both the HAIC and HSHC Procedures, bandwidth below 1 kHz,

above 1 kHz and total were calculated.

(c) Calculation of the Area under the Bandwidth Curve

The frequency response curve of each aid with the high and low frequency limits of amplification specified by the HAIC or HSHC procedure was traced using a Keuffel and Esser Model 4242 planimeter. The areas were not converted to CM^2 and were, therefore, arbitrary units. The reference values, however, were kept constant for each measurement and, therefore, reflect relative relationships. Finally, the ratio of the areas found by the HAIC and HSHC procedure was calculated for each hearing aid.

(4) Harmonic Distortion

The same equipment was used as described for the procurement of the frequency response curve; the gain of each hearing aid was set to 6 dB below its saturation output and the input signal was always 70 dB SPL. The third-octave tracking filter of the B&K type 2112 audio frequency spectrometer was set to automatically measure the energy an octave ahead of the mechanically synchronized B&K Type 1022 beat frequency oscillator. The paper speed of the B&K Type 3205 graphic level recorder was set at 30 mm/sec and writing speed was 100 mm/sec. This measurement always immediately followed that of the frequency response curve, and the tracing of the second harmonic (first = fo) was drawn directly below this curve. The harmonic distortion was quantified by integrating the area under its tracing as in the procedure for bandwidth. Because the bandwidth curves were not delimited at the same frequencies by the HAIC and HSHC methods, only that portion of the second harmonic curve that fell within each of the specified bandwidths was integrated. As a result, there was measured a harmonic distortion area for the HAIC frequency response curve, and a harmonic distortion area for the HSHC frequency response curve.

The ratio of the HAIC or HSHC second harmonic area to its respective HAIC or HSHC frequency response curve area was calculated to provide information as to the relative amount of second harmonic distortion present in a given bandwidth.

(5) Difference Frequency Intermodulation Distortion

The instrumentation show in the block diagram (see Fig. 2 of Smaldino[50] was used to measure second- (quadratic) and third- (cubic) order intermodulation distortion components. The second-order (quadratic) intermodulation distortion component was obtained by the International Telephonic Consultation Committee (CCIF) Method (CCIF 1937 and Peterson[48,49]. Two sinusoidal test signals (f_1 and $f_1 + f = f_2$) of equal amplitude (70 dB SPL) were simultaneously generated and mixed by a General Radio (GR) type 1303 — A two signal generator and the difference in frequency between the two was kept constant at 400 Hz (F). The signal was applied to the speaker in the hearing aid test chamber, where its amplitude was monitored at 70 dB SPL by a condenser microphone and B&K type 2603 microphone amplifier. The output

of the hearing aid located in the test chamber was applied to a B&K type 2112 audio frequency spectrometer and analyzed by a 1/3 octave band accept filter tuned to the difference frequency F (400 Hz). f_1 took the values of .5, 1 and 2 kHz for each aid investigated and correspondingly f_2 took the values of .9, 1.4 and 2.4 kHz. The energy, in dB, observed in the 400 Hz band was designated the quadratic difference frequency intermodulation distortion.

The cubic intermodulation distortion measurements were carried out as above, except that the difference frequency measured at the 1/3 octave filter was of the form $2f_2 - f_1$. So that when, f_1 took on the values .5, 1 and 2 kHz, and f_2 took on the values .9, 1.4 and 2.4 kHz, $2f_2$ was then 1.8, 2.8 and 4.8 kHz and the difference frequencies were 1.3, 1.8 and 2.8 kHz. Since the 1/3 octave filter could not be tuned to the exact difference frequencies, 1.3 kHz was measured at 1.25 kHz, 1.8 kHz, was the average of the measurements at 1.6 and 2.0 kHz and 2.8 kHz was the average of the measurements at 2.5 and 3.15 kHz. The dB output of the filter for each was termed the cubic difference frequency intermodulation distortion.

(6) Speech Noise Intermodulation Distortion

The speech-noise intermodulation distortion was measured by the instrumentation show in Smaldino,[50] Fig. (3). Speech-noise (3 dB) down at 50 Hz and 1000 Hz) was fed into a B&K 1607 which acted as a band reject filter (see Smaldino,[50] Fig. 4 for filter characteristics centered at 1 kHz) centered at .5, 1 and 2 kHz, respectively. The dial position of maximum reject on the B&K 1607 was ascertained by a minimal voltage output measured at a vacuum tube voltmeter. The speech noise, with an effective notch centered at .5, 1 or 2 kHz by the B&K 1607 was fed into the speaker of the B&K 4212 hearing aid test chamber. The level of the noise at the microphone of the hearing aid in the test chamber was monitored by a B&K condenser microphone and B&K type 2603 microphone amplifier at 70 dB SPL. The hearing aid gain was adjusted to 6 dB below saturation output at 1 kHz. The output of the hearing aid was coupled to and transduced by another condenser microphone and fed into a B&K type 2112 audio frequency spectrometer operating as a 1/3 octave band accept filter centered at .5, 1 or 2 kHz. The frequency band rejected by the B&K 1607 was always the band accepted by the B&K 2112 and measured in dB. This measurement specified the speech noise distortion.

(7) Transient Distortion

The hearing aid gain was adjusted to 6 dB below saturation output at 1 kHz. The aid was suspended on a baffle board and a 70 dB SPL square wave click, as monitored by a B&K condenser microphone and type 2603 microphone amplifier, was initiated at intervals of 1-2/second by the Wavetek oscillator (see Smaldino,[50] Fig. 5). A McIntosh 250 amplifier provided the gain to attain the 70 dB SPL in the free field. The amplifier drove a University Model 1D60 driver unit which served as the transducer for the square wave click. The output of the hearing aid under test was applied to a Tektronix oscilloscope

and a Polaroid picture was taken of its waveform. (For outputs of all aids see Smaldino,[50] Fig. 25A-P). To determine the effects of the system on the square wave click, a condenser microphone was put in place of the hearing aid and applied to the oscilloscope. This waveform was photographed and defined the dimensions of the input signal. The photographs of the waveforms generated when a hearing aid was in place defined the output signal. The difference between the input and output signal specified the transient distortion introduced by the hearing aid.

The number of milliseconds (5 msec/division) of prolongation or "ringing" of the input click by the hearing aid was termed the amount of transient distortion #1 for that aid. The measurement was taken at the time between the initiation of the click and the return of the greatest percentage of the waveform to an established baseline (which was, in fact, the trace on the oscilloscope, prior to the click).

Another measure, called transient distortion #2, was taken as the angle formed between the highest peak in the waveform generated by the transduced click and the same baseline as above.

Transient distortion #3 was taken as transient distortion #2 using the midpoint of the largest clumping of peaks.

B. Speech Intelligibility Measures

(a) Preparation of Test Material

The KSU speech discrimination test is made up of eight separate lists (A-H). Each list was passed through the sixteen experimental hearing aids using the instrumentation shown in Smaldino,[50] Fig. 6). The lists, which were on tape, were played by a Tandberg Model 15SL tape recorder through the speaker of a B&K type 4212 hearing aid test chamber. The key words of each list were monitored by a B&K condenser microphone and microphone amplifier to peak at 70 dB RMS at the face of the hearing aid microphone in the test chamber. A 1-kHz calibration tone and then the lists transduced by each hearing aid were applied to a second condenser microphone, fitted with a 2 cc coupler and fed into a B&K type 2112 audio frequency spectrometer. The spectrometer output was fed into a second Tandberg Model 15 SL and recorded at VU=O.

The discrimination test's eight lists were matched with the sixteen experimental hearing aids in a modified latin square design (see Table I). As per this design, there were eleven groups, each group made up of the hearing aid/list combinations as specified.

(b) Subjects

The subjects for this investigation consisted of eleven groups of 20 Navy enlisted men; each man's hearing was screened re: ANSI (1969), and found to be within normal limits. The age composition of each group was approximately the same.

(c) Test Presentation

The test tape for each group of 20 men was played through a Tandberg Model 15 SL tape recorder, each group receiving the aid/list combinations

Table I. Aid/List Composition of the Tapes Presented to Groups 1-11

Group	Aid Number	Respective List
1	1	A-H
2	8	A-H
3	16	A-H
4	1,5,9,13	(A,E),(B,F),(C,G),(D,H)
5	2,6,10,14	(B,F),(C,G),(D,E),(A,H)
6	3,7,11,15	(C,E) (D,G),(A,F),(B,H)
7	4,8,12,16	(D,F),(A,G),(B,E),(C,H)
8	1,2,3,4,5,7,10,13	A,B,C,D,F,G,E,H
9	6,8,9,11,12,14,7,1	C,A,G,F,B,H,D,E
10	15,16,2,3,4,10,11,15	B,C,G,E,F,D,A,H
11	5,9,13,6,14,8,12,16	B,C,D,F,A,G,E,H

shown in Table I. The 70 dB RMS output of the tape recorder was applied to a Grason-Stadler Model 901B noise generator and electronically mixed with speech noise to a signal-to-noise ratio of -2dB. This mixed signal was then applied to twenty Telephonics TDH-39 earphones mounted in Otocups. All testing was conducted in a room with low ambient noise and was monaural to the right ear.

(d) Test Administration

Subjects in each group were seated at desks and each provided an earphone. Each man was provided a pencil and a set of answer sheets (one each of the eight lists composing the KSU test). The order of test presentation was conducted as per Table I. Before beginning the test series, the groups were verbally given the following instructions:

> *"You will be hearing these sentences (point to KSU answer sheet). For each of the thirteen sentences, there are five possible words which you might hear. Please circle the word you think you hear in each sentence. For example the first one might be, 'The baby started to crawl early; if you think you heard crawl, circle crawl; if you think you heard one of the other words, circle it. If you are not sure, guess. The sentences are not numbered and there will be a hissing noise, try and disregard the noise and listen for the words; please listen carefully; they will not be easy to understand. Each list will be introduced by -- This is the KSU Speech Discrimination Test, List A...H, are you ready? And ended by -- That is the end of List A...H. Any questions?"*

The sentences in a list were separated by about a 6 second pause and the presentation of the entire set of 8 lists took about 25 min. Following the test, the subjects were allowed to ask any questions they pleased.

(e) Scoring

Each list was scored according to the method of Berger.[2] Each word missed or unanswered did not have equal error magnitude. For example, if the key words in sentences numbered 6 and 13 were missed or unanswered the discrimination score would be 81% (100-(6+13). Since there are thirteen sentences, even if the subject missed or unanswered every key word, the discrimination score would still be 9%. This 9% was not corrected for, because it was felt by Berger that there was value in having a discrimination test wherein all correct key words would equal a 100% discrimination score.

(f) Derivation of the Best Estimate of Intelligibility for Each Aid

Because of the compromise imparted by the modified latin square design, where not all aid/list combinations were presented to each group, a measure of central tendency for each list was calculated and considered the best single estimate of speech intelligibility through each aid. The mean score for each list A-H was computed collapsing across groups and aids. The median of each one of these calculations was added and an average taken (= the mean median). Deviations of each list median from this mean median were computed and added or subtracted (corrected) from the mean score for each list. These corrected scores were then sorted out according to aid used to produce the score and the scores associated with each group of aids averaged, collapsing now across groups and lists. The mean score, so derived for each aid, was the intelligibility score assigned to each aid, respectively (Table II). e.g.: for List A

List A				Aid #1	
Group #	Aid #	Mean Score	List	Correction Factor	Corrected Score
1	1	65.2	A	+2.1	67.3
2	11	85.7	B	-2.8	87.7
3	22	75.6	C	-1.2	85.3
4	1	66.4	A	+2.1	68.5
5	2	57.4	D	-2.5	76.5
6	4	50.4	E	+2.5	64.5
7	5	56.3	E	+2.5	70.1
8	1	77.1	A	+2.1	79.2

List A				Aid #1	
Group #	Aid #	Mean Score	List	Correction Factor	Corrected Score
9	7	74.2	F	- .5	74.5
10	19	62.6	G	+2.0	74.0
11	16	71.1	H	+9.8	74.3

List A median = 66.4 mean = 74.71

Mean median = 68.5

74.71% was therefore used as the best estimate of intelligibility through Aid #1.

Table II. The Mean Corrected Intelligibility Score, in Percent, For Each Aid Across All List and Aid Combinations

Aid Number	Mean Corrected Score in Percent
1	74.7
2	52.8
3	57.7
4	63.4
5	63.7
6	65.5
7	70.7
8	72.6
9	60.5
10	65.4
11	53.9
12	70.1
13	61.9
14	69.0
15	69.1
16	66.8

RESULTS AND DISCUSSION

A. Statistical Analysis

The 34 electroacoustic characteristics studies are listed in Table III. In order to assess which electroacoustic characteristics most affect speech intelligibility, the raw data were subjected to a multiple regression analysis.

At this point the reader may question that while correlation analyses require linearity of components as a premise to

Table. III

1. Index of Response Irregularity
2. HAIC Bandwidth (Bw1)
3. HSHC Bandwidth (Bw2)
4. Bw1/Bw2
5. HAIC Bandwidth below 1kHz
6. HAIC Bandwidth above 1kHz
7. HAIC Total Bandwidth
8. HSHC Bandwidth below 1kHz
9. HSHC Bandwidth above 1kHz
10. HSHC Total Bandwidth
11. Quadratic Intermodulation Distortion at .5kHz
12. Quadratic Intermodulation Distortion at 1kHz
13. Quadratic Intermodulation Distortion at 2kHz
14. Quadratic Intermodulation Distortion Average .5, 1, 2kHz
15. Cubic Intermodulation Distortion at .5kHz
16. Cubic Intermodulation Distortion at 1kHz
17. Cubic Intermodulation Distortion at 2kHz
18. Cubic Intermodulation Distortion Average .5, 1, 2kHz
19. Speech Noise Intermodulation Distortion at .5kHz
20. Speech Noise Intermodulation Distortion at 1kHz
21. Speech Noise Intermodulation Distortion at 2kHz
22. Speech Noise Intermodulation Distortion Average .5, 1, 2kHz
23. HAIC Harmonic Distortion Area (HD1)
24. HSHC Harmonic Distortion Area (HD2)
25. HD1/Bw1
26. HD2/Bw2
27. Average Signal to Noise Ratio
28. Average White Noise Gain
29. Transient Distortion 1
30. Speech Intelligibility Score
31. Maximum Power (Saturation) Output
32. Gain
33. Transient Distortion 2
34. Transient Distortion 3

their use, the potpourri of measurements taken on the hearing aids under investigation would result in some raw scores which are not linear. The cases in point are those measures taken in decibels; since this scale is logarithmic and not linear, one might object to use of the decibel. The decibel scores were not converted to z (or standard) in this study, primarily because the decibel scale is, in fact, a linear transformation of how the ear analyzes intensity at the levels and frequencies under study here (Harris[17]). Since the ear would, in effect, convert any intensity information into a decibel scale during analysis, a more natural portrayal of the intensity raw data is afforded by a decibel rather than linear scale. Secondly, Hayes[18] points out that, "The value of multiple correlation coefficient is exactly the same ... regardless of whether raw scores or standard scores are involved." The decibel raw scores are then believed to be appropriate for the analyses performed with them.

Table IV in Smaldino[50] shows the Pearson product-moment coefficients (r) for all of the hearing aid performance measurements, and the criterion speech intelligibility scores. From this it can be seen that: (1) Cubic intermodulation distortion (CIM) at 2 kHz, (2) CIM average, (3) CIM at 1 kHz, (4) Speech noise intermodulation distortion at 1 kHz, and (5) bandwidth as specified by HSHC, correlated highest in order from 1-5 with the intelligibility scores.

Since the purpose of this investigation was to determine the best performance predictors of speech intelligibility, it was desirable to choose those performance characteristics which together would have the greatest relation to intelligibility. The 14 highest correlation coefficients (r) were thus selected for the multiple regression analysis (see Table IV).

Table V shows the final multiple r for the 14 characteristics. Since the multiple r of .99 ($F = 4.3$, significant at .01) accounts for all of the variance of the speech intelligibility scores one can assume that the 14 characteristics selected were the ones which had the greatest relation to speech intelligibility.

These pre-selection procedures take advantage of chance high correlations. It might be argued that it must be shown that the same degree of high correlations will occur in another random sample from the same population. Indeed, on the stability of these correlations rests their predictive value to the entire population. While it was not possible to draw another sample in this investigation, the necessity of doing so is recognized. Fourthly, the computer program used to perform the multiple regression analysis allowed a maximum of 14 independent variables. In the absence of the stability of another random sample, the pre-selection of the highest correlations with the criterion, which is the traditional method of data reduction, was thought superior to any other available procedure.

Although this procedure is not a substitute for a cross validation of the multiple r, to eliminate bias due to sampling fluctuations, it does provide some security that the multiple r is accurate even though the analysis was not

Table IV. The 14 Highest Pearson Product Moment Correlations Between Circuit Performance Measurements and Speech Intelligibility

	4	8	15	16	17	18	19	21	22
1	-12	26	28	-15	-11	-00	25	21	27
4		-56	19	47	21	33	13	48	34
8			-15	-30	-25	-26	27	-33	-02
15				67	68	87	45	83	75
16					70	90	41	77	67
17						90	63	82	77
18							56	90	82
19								61	87
21									90
22									
23									
27									
28									
29									
34									
30									

	23	27	28	29	34	30
1	-13	11	17	36	07	-30
4	23	40	25	19	-06	18
8	-01	-10	-07	10	14	-42
15	10	16	82	37	-05	32
16	20	27	69	27	04	54
17	26	-05	86	-16	-38	64
18	21	14	88	18	-15	57
19	49	29	79	-06	-30	23
21	14	20	90	11	-25	43
22	27	27	95	11	-22	27
23		56	33	-09	-41	36
27			24	38	15	18
28				09	-29	39
29					72	-30
34						-35
30						

Table V. Multiple Regression Analysis of the 14 Highest Pearson Product Moment Correlations and Speech Intelligibility (See Legend)

	(B) Beta	Standard Error (B)	Normalized Beta
1	0.30	0.31	2.10
2	0.41	0.33	8.50
3	-0.03	0.27	-0.17
4	-0.40	0.54	-18.74
5	0.44	0.68	21.06
6	2.48	1.14	138.13
7	1.39	0.87	56.01
8	-0.38	0.93	-26.08
9	-2.87	1.29	-178.80
10	-0.67	0.38	-7.81
11	0.88	0.27	61.15
12	-0.04	0.82	-3.86
13	-0.65	0.42	-7.74
14	-0.07	0.34	-1.48

	Regression Coefficient (b)	Standard Error (b)	F Value
1	0.08	0.09	0.99
2	5.46	4.51	1.46
3	-0.00	0.01	0.01
4	-0.23	0.31	0.56
5	0.25	0.39	0.41
6	1.65	0.76	4.75
7	0.72	0.45	2.55
8	-0.27	0.65	0.17
9	-2.03	0.91	4.98
10	-138.69	79.09	3.07
11	36.75	11.11	10.94
12	-0.04	0.70	0.01
13	-0.07	0.05	2.35
14	-0.02	0.11	0.04

Multiple r, +.99

Standard Error of Estimate, +3.14

Degree of Freedom, 1

F Value, 4.33

validated. One caution, however, is described by Nunnally[41] wherein an upward bias on the multiple r can result from a small subject-to-independent variable ratio. The ratio in this study was 6:1, a good deal lower than the 13:1 considered to be unbiased and may account, in part, for the unusually high multiple r.

The value in performing a multiple regression analysis is that in addition to being able to say how much of the variance of the dependent variable is attributable to combinations of the independent variables, the beta values can be used to calculate the relative importance of each of the independent variables to the dependent variable by indicating how much contribution each makes to the overall multiple r. The performance measurements of this investigation were in different units, i.e.: dB, area, msec, Hz, and may not be directly comparable. The beta values, therefore, may not really express the relative contribution of each characteristic to the overall multiple r. While this problem has not been envisioned in other investigations of this sort, and for comparison of results was not taken further in this investigation, it would be preferable in future investigations to convert all measurements into standard scores so that comparisons and further analyses of the data could assume a common reference. In the case of the multiple regression analysis such an assumption gives a more rigorous value to the predictive capabilities of the beta values.

Table VI shows the same sort of analysis as Table V, with all of the regression equations resulting in an F value of 1.5 or less being deleted from the analysis. This procedure allowed only the largest contributors to the multiple r to be considered. As can be seen, and keeping the previous cautions in mind, the multiple r turned out to be .95 with an F of 10.5 which is significant at .01. This means that almost 90 per cent of the variances of the intelligibility scores can be attributed to the variation in the performance measurement of: (1) index of response irregularity (IRI), (2) CIM at 2 kHz, (3) average CIM at .5-1-2 kHz, (4) average speech noise intermodulation at .5-1-2 kHz, (5) signal-to-noise ratio, (6) average white noise gain at .5-1-2 kHz, and (7) transient distortion.

The beta values can be used to derive the variance contribution of each of the performance characteristics to the overall multiple r and can thus be used as a predictor of how much of the variance of the speech intelligibility score is attributed to variation connected with each performance characteristic. This is, indeed, what this study set out to ascertain, i.e., what is the smallest number of performance characteristics of a hearing aid which need be measured to be able to predict speech intelligibility. The beta values shown in Table VI can be converted by the formula; $(B \times r_{xy})^2$ to produce the variance contribution of each performance characteristic to the variance of the speech intelligibility scores, where:

B = each characteristic's beta value

r_{xy} = the r for the same characteristic and the criterion intelligibility score

Table VI. Multiple Regression Analysis of the 14 Highest Pearson Product Moment Correlations and Speech Intelligibility (See Legend)

	(B) Beta	Standard Error (B)	Normalized Beta
1	0.26	0.15	1.80
17	0.95	0.43	45.71
18	1.04	0.40	58.01
22	-0.79	0.37	-49.31
27	0.66	0.14	45.77
28	-0.76	0.48	-69.57
29	-0.53	0.17	-6.30

	Regression Coefficient (b)	Standard Error (b)	F Value
1	0.07	0.041	3.18
17	0.54	0.24	5.02
18	0.69	0.26	4.47
22	-0.56	0.26	4.47
27	27.51	5.95	21.36
28	-0.64	0.41	2.47
29	-0.06	0.02	8.98

Multiple r, +.95

Standard Error of Estimate, +2.72

Degrees of Freedom, 8

F Value, 10.52

The result of calculations of these values for Table VI is shown in Table VII. As can be seen, the variation of CIM at 2 kHz and CIM averaged over .5-1-2 kHz accounts for about 70% of the variance of the dependent variable. It might be concluded, then, that measurement of: (1) CIM at 2 kHz and (2) CIM average in hearing aids would produce the best single predictor of speech intelligibility through that aid. Unfortunately, all is not that simple.

Up to this point, the signs of the correlations analyzed have not been taken into consideration. We find a paradox: The r between the two best predictors of intelligibility, CIM at 2 kHz and CIM averaged over .5-1-2 kHz versus speech intelligibility is positive.

Table VII. Calculation of the Contribution of Each Performance Characteristic to the Total Variance of the Dependent Variable

Characteristic	B	r (with criterion)	$(B \times r_{xy})^2$
1	.95	.64	.37
2	1.0	.57	.33
3	-.79	.27	.04
4	.66	.18	.01
5	-.53	-.30	.03
6	.26	-.30	.006
7	-.76	.39	.09

1 - Cubic IMD at 2 kHz

2 - Cubic IMD Average

3 - Random Noise IMD Average

4 - Signal to Noise Ratio

5 - Transient Distortion

6 - Index of Response Irregularity

7 - Average White Noise Gain

What this logically means is that as CIM increases, so does the speech intelligibility score. From what is known from all previous research (Burnett[6], Olsen[47]) this result is paradoxical. A further review of the table of r's reveals that other positive correlations also have a negative logical meaning and some negative correlations have a positive logical meaning.

Since the multiple r and beta values were calculated from correlations with contrary logical interpretations, the value of using the beta values to determine the contribution of the performance characteristics to the variance of speech intelligibility scores, rests entirely upon whether the problem of those correlations illogical in meaning can be resolved.

B. Rational Analysis

The matrix of r's not only shows how strongly each performance characteristic is related to speech intelligibility, it also shows how strongly they are interrelated with each other. In terms of

the problem this means that illogically positive and negative correlations are correlated with logically positive and negative correlations. That such an analysis produces a high multiple r and accounts for almost all of the variance of the speech intelligibility indicates that most of the performance characteristics important to speech intelligibility through a hearing aid were tapped by this procedure. What is not known is the route by which these characteristics interact to produce high correlations in an illogical direction.

It is clear that the two CIM measures are expectedly highly intercorrelated, for they are certainly measuring the same thing. What is significant is that they are also highly correlated with white noise gain, the correlation of which with speech intelligibility is in a logically correct direction in distinction to the CIM measures and because of its beta value is probably measuring something different from CIM. Other occurrences of this sort are common in the data and prompt one to make the following conjecture as to the incidence of high correlations with illogical meanings: The route by which CIM affects speech intelligibility is unclear because of the pattern of possible correlations with other performance characteristics which are logically positive in meaning and therefore beneficial to speech intelligibility through hearing aids. In addition, the possibility exists that the relative importance of each performance characteristic to intelligibility is dependent upon the kinds, intensities and proportions of the other characteristics present. A general statement, therefore, as to which electroacoustic characteristics are most important to speech intelligibility is not possible without information regarding the type and degree of the other characteristics, and a formula for determining which characteristics will be working to affect speech intelligibility. Such an hypothesis can be used to partly explain the lack of unanimity in previous investigations relative to the important performance characteristics for speech intelligibility. In each investigation, performance characteristics may have interacted in a different way, allowing different performance characteristics to appear as most critical to intelligibility.

C. Further Rational Analysis

Since the route by which the correlations negative in meaning affected speech intelligibility could not, at this time, be identified, a multiple regression analysis of those performance characteristics that are known to be meaningfully positive in relation to intelligibility or which have a meanfully positive relation to intelligibility in this data was thought to provide some insight into the route by which intelligibility is degraded or enhanced by the investigated performance characteristics. In addition, the meaningfully positive correlations may be found to have good predictive value for intelligibility through hearing aids.

The table of r's reveals four performance characteristics meaningfully positive in relation to intelligibility (for this selection any r below .20 with the criteria was disregarded because of the weak relationship.) This is not to say, however, that with another group of

aids, using a different intelligibility test and a different degradation besides speech-spectrum noise, the characteristics found to have a low r with criteria in this data would be low in other data. The four characteristics and their logical meaning are as follows:

1. Index of Response Irregularity – (r = -.30) – As the response curve becomes more irregular with valleys and peaks the index gets higher. Concomitant with response irregularity are resonance peaks, harmonic and intermodulation distortions. It would be expected that these acoustic events would have a degrading effect upon intelligibility. The negative correlation with intelligibility indicates that the expected effect did occur which is meaningfully positive.

2. Houston Speech and Hearing Center (HSHC) Bandwidth Below 1KHz - (r = .42) Liberman[29,30] has shown that the high-frequency, low-intensity second formant transitions of the speech signal cue consonant discriminations and are therefore important to speech intelligibility. Martin, Pickett and Coltan[39] have shown that the energy present in the low-frequency, high-intensity first formant can mask the critical second formant transitions and thus reduce consonant discriminations. In a hearing aid with an extended low-frequency response (bandwidth below 1 kHz) the energy present in the first formant is likely to be amplified and have a relatively large masking effect upon speech intelligibility. The negative correlation bears this out: we would expect reduced intelligibility with extended low frequency bandwidth, this, then, is a meaningfully positive result.

3. Average White Noise Gain – (r = +.39) – It is known that high-gain hearing aids contribute relatively less distortion than low-gain instruments at settings less than full gain. Secondly, it is known that intelligibility is critically dependent upon intensity; if an instrument cannot amplify speech above a minimal S/N, intelligibility is diminished. In either or both conditions intelligibility should be meaningfully positive in its correlation to intelligibility, as is the case here.

4. Transient Distortion – (r = -.30) – Transient distortion is an overall measure of all the nonlinearities occurring in a hearing aid. The higher the transient distortion then the lower should be the intelligibility score. This is, in fact, the effect here.

Table VIII shows the Pearson r's for these four performance characteristics. The intercorrelations are low which indicate that each characteristic is relatively independent in its relation to speech intelligibility and that it is, therefore, measuring different hearing aid performance characteristics. High intercorrelations would have indicated that only one characteristic was being measured and that one would not have as good a predictive value in determining what combinations of performance characteristics are most important to speech intelligibility.

Table IX shows the multiple regression analysis of the four characteristics. With previous cautions in mind, the multiple r of .65 (F of 2.04 significant at .01) is probably biased upward; 42% of the variance of the speech intelligibility scores can be accounted

Table VIII. Pearson Product Moment Correlations Between the Four Logical Meaningful Hearing Aid Performance Measurements and Speech Intelligibility

	2	3	4	5
1	26	17	36	-30
2		-07	10	-42
3			09	39
4				-30
5				

1. Index of Response Irregularity
2. HSHC Bandwidth below 1 kHz
3. Average White Noise Gain
4. Transient Distortion 1
5. Speech Intelligibility

for by the variances of these four characteristics. When the beta values are plugged into the formula, $(B \times r_{xy})^2$, the results (indicating how much variance each characteristic contributes to the multiple r) are shown in Table X. From this table it may be concluded that average white noise gain and HSHC bandwidth below 1 kHz contribute most to the variance of the speech intelligibility scores. Transient distortion and index of response irregularity contribute about equally less. What this means is that if just these four characteristics are measured on a group of communication circuits a multiple r of .65 can be predicted within the limits of the standard error of the multiple r, in this case 5.62 (from Table IX). Of these a high white noise gain and reduced HSHC bandwidth below 1 kHz will

Table IX. Multiple Regression Analysis of Logically Meaningful Correlations with Speech Intelligibility

(B) Beta	Standard Error (B)	Normalized Beta
-0.20	0.26	-1.41
-0.31	0.24	-1.83
0.42	0.23	38.72
-0.23	0.24	-2.81

Regression Coefficient (b)	Standard Error (b)	F Value
-0.06	0.07	0.64
-0.01	0.01	1.72
0.36	0.20	3.28
-0.03	0.03	0.92

Multiple r, +.65	1. Index of Response Irregularity
Standard Error of Estimate, +5.62	2. HSHC Bandwidth below 1 kHz
Degrees of Freedom, 11	3. Average White Noise Gain
F Value, 2.05	4. Transient Distortion 1

Table X. Calculation of the Contribution of Each Logically Positive Performance Characteristic to the Total Variance of the Dependent Variable

Characteristic	B	r (with criterion)	$(B \times r_{xy})^2$
1	.21	-.30	.063
2	-.31	-.42	.130
3	.42	.39	.164
4	-.24	-.30	.072

1 - Index of Response Irregularity

2 - HSHC Bandwidth below 1 kHz

3 - Average White Noise Gain

4 - Transient Distortion

have the highest re...ionship to speech intelligibility. To a lesser extent, low transient distortion and index of response irregularity are also desirable characteristics. In predicting, then, in the clinic which electroacoustic characteristics are most desirable to enhance speech intelligibility, at least, the above four are important. Other meaningfully negative characteristics may also be important, but before the route by which they affect intelligibility can be identified, much work must be done, and at the moment their predictive value is greatly reduced.

SUMMARY AND CONCLUSIONS

This study was conducted to ascertain the effect on speech intelligibility of 34 electroacoustic characteristics of communications circuits. Sixteen hearing aids of various brands and vintages, representing poor to good speech transmission systems, were subjected to a battery of physical measurements. The KSU speech discrimination test was recorded through the same 16 circuits and presented to 220 listeners. The results were analyzed statistically and logically.

A. The conclusions drawn from the multiple regression analysis of the 14 characteristics with the highest correlation with speech intelligibility are:

1. The high multiple r of .99 derived from these characteristics suggests that most of the performance characteristics important to speech intelligibility were tapped in this investigation. It must be cautioned, however,

that the small subject-to-independent variable ratio and preselection of data with high correlations may have biased the multiple r upward.

2. Of the 14 characteristics, cubic intermodulation distortion of 2 kHz, and averaged over 0.5 - 2 kHz, by virtue of their high beta values, contribute most to the variance of the speech intelligibility scores and, therefore, are judged to be the best predictors of how well an aid will transduce speech; however, these correlations are logically absurd, since circuits with the most distortion yielded best intelligibility.

It was hypothesized that the influence of a particular electroacoustic characteristic exerts on speech intelligibility is tempered by its intercorrelations with other characteristics, both beneficial and degrading to speech intelligibility. The route by which these interactions take place was not identified, but may take the form of a formula taking into account kinds, proportions and intensities of various characteristics occurring in a particular hearing aid.

B. The conclusions drawn from the logical analysis are as follows:

Since the route by which the logically negative correlations affect speech intelligibility could only be conjectured, a multiple regression analysis of those performance characteristics known to have a logically positive correlation from previous research, or from the data of this investigation, was completed. The performance characteristics so selected were: Index of Response Irregularity, HSHC bandwidth below 1 kHz, average white noise gain, and transient distortion. These four characteristics produced a multiple r of .65 with an F value of 2.05 which is significant at .01. The beta values indicate that average white noise gain and HSHC bandwidth below 1 kHz contribute most to the variance of the speech intelligibility scores. In terms of communications circuit design characteristics, this suggests that for normal listeners and for such speech discrimination tasks, a circuit should have a high average white noise gain, reduced bandwidth below 1 kHz, a fairly flat frequency response, and low transient distortion in order to yield high speech intelligibility. In addition, the low intercorrelations and high multiple r suggest that these four measures are relatively independent in their affect upon speech intelligibility.

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